The BOLD response during Stroop Task-like inhibition paradigms:

Effects of task difficulty & task-relevant modality

Running Head: Modality effects on the neural mediation of attention?

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Abstract

Previous studies of the Stroop task propose two key mediators: the prefrontal and cingulate cortices but hints exist of functional specialization within these regions. This study aimed to examine the effect of task modality upon the prefrontal and cingulate response by examining the response to colour, number and shape Stroop tasks whilst BOLD fMRI images were acquired on a Siemens 3T MRI scanner. Behavioural analyses indicated facilitation and interference effects and a noticeable effect of task difficulty. Some modular effects of modality were observed in the prefrontal cortex that survived exclusion of task difficulty related activations. No effect of task-relevant information was observed in the anterior cingulate. Future comparisons of the mediation of selective attention need to consider the effects of task context and task difficulty.

Keywords

Attention, prefrontal cortex, cingulate cortex, fMRI, task modality, task difficulty, Stroop task

Introduction

The Stroop Task

Since its inception in 1935 (Stroop, 1935), the Stroop task has become one of the most well known and widely used cognitive tests (Macleod, 1991), and is now considered to be one of the premier tests of selective or inhibitory attention. In the classic version of this test, participants are required to name the ink colour in which stimuli are displayed. In the neutral condition these stimuli have consisted of solid colour squares, rows of X's, or neutral words. In the congruent condition, the stimuli consist of colour words printed in matching colour inks, whilst in the incongruent condition colour words are printed in *non*-matching ink colours. By comparison to the mean response time in the neutral condition, two effects are noticeable; an interference effect and a facilitation effect. The Stroop interference effect ('the Stroop effect') refers to the observation that participants are generally slower to name ink colours in the incongruent condition than in the neutral condition, because they are distracted by reading, which is more automatic than colour naming and thus more difficult to inhibit (Macleod & MacDonald, 2000). The term 'Stroop facilitation effect' is derived from observations that participants are faster to name the ink colours of stimuli in the congruent condition compared to those in the neutral condition.

Neural Mediators

As our knowledge of psychological bases of the Stroop phenomena continues to grow, more recent studies have begun to dissect which brain regions are required for its performance. In 1990, Pardo, Pardo, Janer, and Raichle became the first to take advantage of positron emission tomography in an attempt to clarify which brain regions mediate selective attention. In their comparison of neural mediation during the incongruent condition minus that observed during the congruent condition, activity was strongest in the anterior cingulate cortex (ACC). However, this early study lacked control for colour naming (since a neutral colour naming control condition was not included for comparison) and an extensive network of other regions was activated. Since this original study, there have been many further neuroimaging studies, more recently employing the finer spatial resolution of functional magnetic resonance imaging. Whilst activation of the prefrontal (PFC) and cingulate cortex (CC) have frequently been observed, the site, extent and intensity of these activations has varied from one study to the next, as have the conditions being compared.

Between-Study Variability

In the PFC, some studies have demonstrated broad PFC activity (Banich et al., 2000a; Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Larrue, Celsis, Bès, & Marc-Vergnes, 1994; Leung, Skudlarski, Gatenby, Peterson, & Gore, 2000; Milham et al., 2001; Milham, Banich, & Barad, 2003a; Taylor, Kornblum, Lauber, Minoshima, & Koeppe, 1997), some studies have reported more selective, dorsolateral PFC (dlPFC) activity (Milham, Banich, Claus, & Cohen, 2003b), and others have only demonstrated non-dorsolateral PFC activity (Bench et al., 1993). The original study by Pardo et al. (1990), failed to find any significant PFC activation and Bench et al. (1993) reported that the degree and distribution of PFC activity varied according to the chosen experimental parameters.

In the CC, many Stroop task studies have demonstrated activation of the ACC (Barch et al., 2001; Bench et al., 1993; Carter et al., 2000; Fan et al., 2003; Gruber, Rogowska, Holcomb, Soraci & Yurgelun-Todd, 2002; Leung et al., 2000; Milham et al., 2001, 2003a, 2003b; Pardo et al., 1990; Peterson et al., 2002; Ruff, Woodward, Laurens & Liddle, 2001), in either the perigenual or midcingulate division. Although the bulk of evidence favours activation of the ACC, there have been isolated reports of increases in the posterior cingulate cortex activity (PCC) (Bench et al., 1993; Milham et al., 2003a; Steel et al., 2001). Activation of the ACC by Stroop task paradigms may be subject to the effects of experimental parameters to an even greater degree than the PFC (Banich et al., 2000a; Carter et al., 2000; Mead et al., 2002; Milham et al., 2001).

Functional Specialisation

These sources of between-study variability proved difficult to explain under previous theories of the neural bases of selective attention, causing some researchers to question the robustness of the specificity of these findings. To some extent, the literature described so far alludes to differences *between* the CC and PFC in their involvement, however, there are now growing suggestions of functional specialization *within* the CC and PFC. A new body of research is emerging which suggests that adaptations of the Stroop task can be used to demonstrate functional specialization of these regions (Bush, Luu, & Posner, 2000). For example, Gruber et al. (2002) observed that signal intensity was significantly increased in the perigenual cingulate region when contrasting regions activated more by incongruent stimuli than by colour naming, whereas the difference in activity between these conditions in the midcingulate region was not significant. From their interregional correlational analyses of ACC activity during the Stroop task, Peterson et al. suggested that the ACC integrates the activity of multiple attentional subsystems (Peterson et al., 1999). Despite these findings, support for functional specialization in the ACC is not unequivocal. In their investigation of Stroop task induced functional specialization with a 1.5T system, Barch et al. (2001) found that vocal and manual response modalities activated similar ACC regions (incongruent condition – neutral condition), and that verbal and spatial processing modalities (of the same composite stimuli) again activated similar ACC regions (incongruent condition – neutral condition). However, although they failed to demonstrate modular ACC specialization, Barch et al. recommended that it might be detected with a higher resolution MRI system.

Functional specialization of the PFC in Stroop task paradigms is not as widely studied, but reports from the Banich et al. group suggest that it may also display modular specialization. Banich et al.'s (2000b) reported that their classic Stroop task yielded significant activity in the ventral PFC and that in contrast, a spatial-word task (lexical task-irrelevant dimension) yielded significant dorsal PFC activity. Based on these results they suggested that PFC activity was sensitive to the effects of task-relevant modality during the Stroop task and that it may therefore be necessary for the attentional set needed to impose top-down control, in order to selectively attend to task-relevant information. This isolated explicit demonstration of distinct PFC activations according to task-relevant modality requires replication. Furthermore, the widespread generalisability of the modularity conclusions requires repetition in an extended range of modalities. In a separate study, Banich et al. provided evidence that PFC activity during Stroop tasks (specifically lateralisation) was also sensitive to other modality effects (Banich et al., 2000a). In their colour-word task they reasoned that attentional set was more difficult to impose when attending to colour (and inhibiting colour word reading) rather than when attending to colour words. In a second, colour-object task, stimuli consisted of pictures of objects, displayed in a high association colour in the incongruent condition (e.g. a red strawberry) or as in the neutral condition, a low association colour (e.g. a yellow flower – an object not strongly associated with any colour). They similarly reasoned for their colour-object task that attentional set was more difficult to impose when attending to the object (and inhibiting colour naming) than when attending to colour. Whereas they noted left PFC activity in the version of the colour word task for which attention was difficult to impose, for the difficult form of the colour object task, right PFC activity was noted instead. Alternatively, these findings could be interpreted as reflecting task-difficulty related differences in PFC activity as opposed to true modality-related effects. Further studies of interactions of the CC and PFC with selective attention could clearly be informative with regards further knowledge of the range of functions subserved by these regions, the manner or circumstances in which they operate, and the organisation of functions within them.

Support for Functional Specialisation from Related Tasks

Studies of other variants of the Stroop task do lend support to the idea that task-relevant modality might affect the pattern of CC and PFC response, however, in relation to this hypothesis, omissions and confounds are widespread. In Bush et al.'s study (Bush et al., 1998) number words were displayed an incongruent number of times on screen and participants were required to indicate the number of words on screen irrespective of word meaning. This paradigm (incongruent condition – neutral words) activated the ACC but not the PFC. However, they did not include a **direct** comparison of their number Stroop task with a colour Stroop task and they did not examine the neural bases of Stroop facilitation in their new paradigm. Although Barch et al.'s comparison of task relevant modality involved well-matched stimuli since they compared spatial and verbal attributes of the same stimuli, both the task relevant and irrelevant modalities varied between modalities (Barch et al., 2001). Taylor et al. (1997) directly compared the neural mediation of the classic Stroop task and the more recent emotional Stroop task, in which emotional words are displayed in different colour inks and reading again interferes with colour naming. Significant activation common to both experiments did not include PFC or CC regions. However, both task relevant modality and the nature of the non-lexical comparison condition differed between the experiments; a fact that may have exaggerated differences in the regions activated and thereby lessened the likelihood of common activations. Furthermore, whilst in the classic Stroop interference exists between the task relevant and irrelevant dimensions, emotional Stroop task stimuli do not contain inter-dimensional conflict. The cognitive interference paradigms compared by Fan et al. (2003) (flanker task, word-word Stroop task and spatial conflict task) and Peterson et al. (2002) (Stroop task and Simon task) contained clear sources of inter-dimensional conflict, and appeared to suggest that a similar network of regions was recruited in each instance (although the exact location of PFC and CC regions varied), but the paradigms compared did not just differ with regards to task-relevant modality, they were fundamentally different. None of their comparison tasks contained lexical information, whereas lexical information was an integral part of the Stroop task that each compared to.

Aims and Hypotheses

In summary, whilst current literature supports the involvement of the PFC and ACC in mediation of the Stroop task (albeit less consistently for the latter), there is considerable variation in the occurrence, location and significance value of activity within these regions. Behavioural studies have already suggested that the Stroop effect is not a unitary phenomenon. Similarly, the neuronal response to the Stroop task is seemingly variable. These inconsistencies have recently culminated in the suggestion that task relevant modality may affect the pattern of neural mediation. However, these comparisons have been confounded by for example, use of paradigms that differed in more than one respect and further proof of modular organisation is required. Clearly, unless the effects of task relevant modality are compared in a systematic and controlled manner, the effects of task modality on mediation of the Stroop task will remain unclear. Accordingly, the aim of the present study was to determine the effects of task relevant modality upon the BOLD response to the Stroop task (particularly in the PFC and CC) by holding the task irrelevant dimension constant and varying only the task relevant dimension. This study thus aimed to test the common assumption that selective attention is performed by a unitary process that is invoked regardless of task relevant modality. It was predicted that task modality would affect the pattern of Stroop task-related activation within the CC and PFC, i.e. it was expected that each modality would activate different subdivisions of these regions. PFC - CC differences in the existence or organisation of modular task relevant processing would serve the secondary aim of further delineating the respective roles of these regions in these types of tasks.

Materials and Methods

Following procedures specified by the University of Reading's Ethics and Research Committee, this study was independently scrutinized and subsequently granted ethical approval.

Participants

Fifteen healthy young adults were recruited from the undergraduate population in the School of Psychology, University of Reading (four males, eleven females). Their mean age was 23.3 years ($\pm$ 6.31) and all of them were right handed. All participants gave informed consent and were paid £ 20 for their participation. Those who suffered colour blindness or uncorrected visual acuity deficits were excluded, as were those with a psychiatric or neurological history, those who had experienced head injuries or long periods of unconsciousness, and those with a history of alcohol or drug abuse.

Experimental Paradigms

Participants were asked to perform three versions of the classic Stroop task (Stroop, 1935): a colour task, a number task and a shape task. As in most previous studies, a stimulus/response set of 4 items was used. In Stroop task paradigms it has been suggested that a manual response is a more accurate indicator of the effect of task condition than a verbal response (Barch et al., 2001). A manual response mechanism was also preferable to (i) enable comparison with the majority of pre-existing literature, and (ii) because the head movement associated with verbal responses may cause significant confound in fMRI studies. Thus in the colour Stroop task, participants were required to identify the ink colour in which each word was displayed. Participants were instructed to indicate their response via an MRI compatible response box held in their right hand (LUMItouch™, Photon Control Inc., Burnaby, Canada), pressing button 1 with their first finger if the stimulus was displayed in green, pressing button 2 with their second finger if it was displayed in blue, button 3 with their third finger if it was displayed in red and button 4 with their fourth finger if it was displayed in purple. In the neutral condition, a row of four X's was presented in the centre of the screen. ACC activity can sometimes disappear when lexical stimuli are used in the control condition (Mead et al., 2002; Taylor et al., 1997). It was therefore decided to use a row of four X's, and to ensure that this choice was consistent across modality. In the congruent condition, the colour words green, blue, red and purple were presented in the centre of the screen in the same ink colour, and in the incongruent condition, these colour words were presented in ink colours that were part of the response set (i.e. green, blue, red and purple) but did not match the colour word. The number version was similar to that employed by Bush et al. (1998) except for their use of a lexical control. Here participants' task was to indicate the number of words displayed, by pressing the corresponding button on the response box. In the neutral condition a row of four X's was presented a varying number of times on screen, in the congruent condition, number words were presented the same number of times as the number word, and in the incongruent condition, number words were presented a different number of times to the number word. In the shape Stroop task, participants had to identify the geometric shape (circle, square, triangle, rectangle) in which the stimulus was presented. In the neutral condition, a row of four X's was presented inside a geometric shape. In the congruent condition a shape word was presented that matched the geometric shape it was displayed inside, and in the incongruent condition a shape word was presented which did not match the geometric shape it was displayed inside. Table 1 depicts example stimuli from each condition of each task. Thus in all three tasks, the task relevant modality varied (colour vs. number vs. shape), but unlike some previous neuroimaging studies of Stroop-like phenomena (e.g. Fan et al., 2003; Peterson et al., 1999), the task irrelevant or interference dimension was consistently linguistic. Consistent use of a verbal task irrelevant dimension had the added advantage of reducing any between-task lateralisation confounds. In the incongruent condition of each task version, the Stroop interference effect was consistently due to semantic interference between the task relevant and task irrelevant dimensions.

Stimuli were projected via a Sanyo Multimedia PLC-XP40L projector onto a screen at the rear end of the magnet bore, 71.6 cm away from a mirror on top of the head coil which reflected the image down towards participants' eyes. Courier New Font 24 point was used for the verbal aspects of stimuli in all tasks. In the colour modality the stimuli subtended an angle of 0.48 ˚, in the number modality the maximum angle subtended was 2.9 ˚, and in the shape modality the maximum angle subtended was 4.3 ˚. Comparable stimulus presentation times were used to those employed in the original study by Pardo et al. (1990) and many subsequent studies. Thus stimuli were displayed for 1300 ms each, with a 350-ms gap in-between. Participants were told in advance that new stimuli would be presented every 1.65s to prepare them for how quickly they needed to respond. To avoid participants using strategies such as blurring their vision to reduce interference from word reading, participants were asked to keep the stimuli in sharp focus (Bush et al., 1998; Fan et al., 2003). Participants were also requested to respond quickly and accurately. Twenty stimuli were presented in each block, with a 360-ms gap before the next block. Within each experiment there were four blocks of the neutral condition, four blocks of the congruent condition and four blocks of the incongruent condition, arranged in four block repetition phases such that each phase contained one block of each of the three conditions. A block design has been used by the majority of neuroimaging studies of the Stroop task so far, and was preferred to an event-related design to increase the chances of detecting adequate BOLD signal (Liu, 2004). Furthermore, whilst some researchers (e.g. Carter, Mintun, & Cohen, 1995; Milham et al., 2001) have preferred the use of blocks of incongruent/congruent trials mixed with a proportion of neutral trials to prevent the development of interference suppression strategies or expectation effects, adoption of this adaptation risks weakening the resultant significance of differences in BOLD response between the experimental and neutral conditions. Each experiment began and ended with a fixation block, also lasting 33.36 s, with the aim of predisposing participants towards central fixation. The fourteen blocks in each experiment were counterbalanced according to one of six order lists, as was the order of the tasks themselves. Within each order list, the neutral, congruent and incongruent blocks appeared in a different order in each of the four block repetition phases. Between the order lists, no order of neutral, congruent and incongruent blocks appeared in the same block repetition phase as any other order list. Each task was preceded by a short practice session using stimuli from all conditions, to familiarize participants as to which response keys corresponded to each colour, number or shape. Reminders present on screen throughout each task were piloted to assist participants in remembering the button coding systems, but were not used in the study proper, following comments that they were distracting.

Acquisition of Neuroimaging Data

Blood oxygenation level dependent (BOLD) contrast images were acquired on a 3T Siemens Magnetom Trio running on Siemens' Syngo software version VX22A (Siemens Medical Solutions, Bracknell, U.K.), in conjunction with an 8 array head coil (USA

Instruments, Ohio, USA). To limit excessive head movements, the area between participants' heads and the head coil was padded with foam and participants were asked to remain as still as possible. Snugly fitting headphones (MRConfon, Magdeburg, Germany) dampened background scanner noise and enabled communication with participants whilst in the scanner. The interleaved EPI sequence incorporated a TE of 30 ms, which at 3 T is known to produce good quality BOLD images and reduce serious susceptibility artefacts (Deichmann, Josephs, Hutton, Corfield, & Turner, 2002). Images were acquired in the transverse plane, but at a 30 ° tilt away from the horizontal axis (towards the dorsal surface of the brain), to minimize signal loss in inferior frontal lobe regions due to frontal sinus local susceptibility gradients (Deichmann, Gottfried, Hutton, & Turner, 2003). Forty eight 2 mm slices alternating with a 1mm gap ensured whole brain coverage and effectively gave 3 mm isotropic resolution (3-mm^3 voxels), whilst minimizing spin excitation history effects caused by intra-volume acquisition head movement (Williams, Howard, Frackowiak, & Turner, 1996). The FoV was 192 mm. Use of the 8-array head coil permitted the deployment of Siemen's parallel acquisition technique iPAT (Sodickson & Manning, 1997), which improves imaging speed by allowing undersampling of k-space. In this study iPAT technology was deployed in conjunction with generalized autocalibrating partially parallel acquisition (otherwise known as GRAPPA; Griswold et al. 2002) via the acquisition of auto-calibration signal lines with an acceleration factor of 2. Thus the TR of the acquisition sequence was 2780 ms. Use of a TR of time period different to that for which the stimuli were presented had the advantage that sampling artefacts were reduced by acquiring the volumes at different parts of the stimulus processing cycle. With 12 volumes being collected per experimental condition and 168 volumes being collected overall, the total scan time was 7 min 47 s for each task.

At the beginning of image data collection proper, the first radio frequency pulse generated by the scanner triggered Eprime to begin displaying stimuli, thus synchronizing stimulus presentation and data collection. During each acquisition Siemen's 'MoCo' corrected for intra-scan movement retrospectively, via standard 6 body affine transformations, and the PACE algorithm (prospective acquisition correction; Thesen, Heid, Mueller, & Schad, 2000) reduced motion-induced effects on magnetization history by adjusting slice position and orientation prospectively. Due to technical difficulties, imaging data from the number Stroop task was only available for 14 participants, and data from the shape Stroop task was only available for 13 participants.

Anatomical data were collected in the same orientation and plane as the functional data to facilitate neuroanatomical localization using an MP-RAGE (Mugler & Brookeman, 1990) single-shot T1-weighted sequence with one hundred and seventy six 1 mm slices through the brain alternating with a 0.5 mm gap. The sequence incorporated a TR of 1830ms a TE of 4.43 ms, and a FoV of 256 mm. The structural sequence also employed iPAT technology and a GRAPPA acceleration factor of 2.

Analyses

During the course of the study, participant comments suggested that the three versions of the Stroop task were not of equal difficulty. With the view that any differences in effect at the behavioural level may aid interpretation of the neuroimaging data, it was decided post-hoc, to perform a two-way (repeated measures) general linear model analysis to determine the main effect of task-relevant modality along with the main effect of condition type and any interactions between these two variables. This analysis was performed once for performance accuracy (percentage correct) and once for mean reaction time. Where Mauchly's test of sphericity was significant at $p<0.05$, the Greenhouse-Geisser correction was employed. Planned comparisons were used (where appropriate) to ascertain more precisely which aspects of the data were significantly different from one another.

To determine the effect of task-relevant modality upon brain regions recruited during performance of the Stroop task, the neuroimaging data were analysed using SPM2 (Friston et al., 1995). For each participant, these data were first corrected for potential slice timing errors by synchronizing each slice in each volume to the middle slice in the acquisition sequence. Next the images were spatially realigned to the first image in the series using an automatic sum of squares minimization algorithm to attenuate the effects of intrascan head movement (Ashburner & Friston, 1997). All subjects remained still during the scanning sessions, no subject displaying more than a millimetre movement or a degree rotation from the reference image. Stereotactical normalization to the Montreal Neurological Institute template accounted for neuroanatomic variability and facilitated inter-participant comparisons and production of a mean group image (Ashburner & Friston). Finally, the data were smoothed using a Gaussian kernel with a FWHM of 8 mm to increase the signal to noise ratio according to the matched filter theorem.

Following preprocessing, a design matrix was constructed incorporating convolution of the experimental design with a haemodynamic response function (including time and dispersion derivatives) to model the haemodynamic lag in response behind changes in neuronal activity. Realignment parameters built into the design matrix as regressors to attenuate residual movement-related artefacts that could not be corrected by the rigid transformations applied earlier. This model was then estimated in a first level analysis that used proportional scaling to remove global effects and a high pass filter of 133.44 s (TR x number of scans per epoch x number of conditions). Application of this design matrix yielded one mean image per contrast per participant, one contrast for the facilitation comparison and one contrast for the interference comparison. In keeping with the use of these terms in the behavioural literature, the facilitation contrast hereby refers to regions activated in the congruent condition to a greater extent than in the neutral condition, and the interference contrast hereby refers to regions activated in the incongruent condition to a greater extent than in the neutral condition.

Using a mean group contrast image, a random effects, second level analysis was performed to enable inferences to be drawn about population wide effects, based on the theory of random Gaussian fields. A three-level one-way ANOVA analysis of (BOLD contrast) voxel values generated in the first level analyses determined whether there was a main effect of task modality and the activations associated with the facilitation and interference contrasts within each modality. To accurately determine between modality differential activations, each pair of modalities was then compared to determine in which voxels the activity in one modality was significantly different from that in the other.

Within the CC and PFC, the cognitive ACC and dlPFC were of particular theoretical interest and indeed, these subregions are most frequently associated with the mediation of the Stroop task (see introduction). Supplementary region of interest (ROI) analyses were therefore performed using MarsBaR (Brett, Anton, Valabregue, & Poline, 2000) for each contrast in each modality, to test the hypotheses of task-modality induced differential activation in these specific regions. dlPFC and cognitive ACC ROIs specifications were taken from Bishop, Duncan, Brett, and Lawrence (2004): 16-mm diameter sphere at ±34,36,24 for the dlPFC ROI and a 16-mm diameter sphere at ±4,14,36 for the cognitive ACC ROI. Analyses of the cognitive ACC ROI were performed separately for each participant and each modality, and then repeated for the dlPFC ROI. ROI t statistics for the participants were then entered into a one-way ANOVA comparison to test for a main effect of modality on the significance of activity within each ROI. Where necessary Tukey’s post hoc tests were implemented.

To separate direct effects of task relevant modality from those of task difficulty (an indirect effect), a parametric map of those brain regions in which differential activation correlated with performance accuracy was derived. To generate this map mean-centred percentage performance accuracy was first calculated for participants, for each modality. These data were then entered as a covariate in a simple regression analysis to produce the parametric map of task difficulty effects. The ANOVA analysis of the main effect of task-relevant modality was then repeated using the performance accuracy map as an exclusive mask (at p=0.05) to determine differential activations produced by the between modality comparisons, independent of the effects of differences in performance accuracy. This procedure was performed separately for the facilitation and interference comparisons.

In the results that follow, Z values are thresholded at 3.09, corresponding to a significance level of $P<0.001$, uncorrected. The coordinates of these activations are summarized in the standard stereotactic space of Talairach and Tournoux (1988). Following use of “mni2tal” to convert the Montreal Neurological Institute coordinates produced by SPM (Evans, Collins, & Milner, 1992) to the Talairach and Tournoux coordinate system (see Brett, 2002). A contiguity threshold of 10 active voxels (Forman et al., 1995) was employed to help protect against false positives due to multiple comparisons.

Results

Behavioural Results

At debrief, no participants reported the use of specific strategies to ‘override’ the inherent interference effects. Table 2 summarizes the descriptive statistics pertaining to the behavioural results. The inferential statistics revealed a significant main effect of testing condition upon performance accuracy ($F(2,28)=27.30$, $p<0.001$) and reaction time ($F(2,28)=19.23$, $p<0.001$). In general, participants were faster to respond in the congruent condition than in the neutral condition (a facilitation effect)($F(1,14)=141.55$, $p<0.001$) and slower to respond in the incongruent condition than in the neutral condition (an interference effect)($F(1,14)=8.77$, $p<0.01$). These results are comparable with those obtained in previous neuroimaging studies of the Stroop task (e.g. Barch et al., 2001; Fan et al., 2003). Analyses of performance accuracy revealed that participants were also more accurate in the congruent condition than in the neutral condition ($F(1,14)=11.89$, $p<0.005$) and less accurate in the incongruent condition than in the neutral condition ($F(1,14)=11.76$, $p<0.005$). A significant main effect of task modality was observed for both performance accuracy ($F(2,28)=5.81$, $p<0.01$) and reaction time ($F(2,28)=10.81$, $p<0.05$). Participants performed more accurately in the number modality than in the colour ($F(1,14)=5.66$, $p<0.05$) and shape modalities ($F(1,14)=16.88$, $p<0.01$). The differences in performance accuracy between the colour and shape modalities were not significant ($F(1,14)=0.02$, $p=0.90$). Participants were also faster to respond in the number modality than in the colour ($F(1,14)=17.86$, $p<0.001$) and shape modalities ($F(1,14)=28.64$, $p<0.001$). However, there were no significant differences in reaction time between the colour and shape modalities ($F(1,14)=0.69$, $p=0.42$). For both the performance accuracy and reaction time analyses there were no significant interactions between modality and condition ($F(4,56)=0.27$, $p=0.89$ and $F(4,56)=0.53$, $p=0.50$ respectively, i.e. the effects of condition on reaction time or performance accuracy were similar in each modality.

Neuroimaging Results

The Effect of Task Relevant Modality Upon Neural Facilitation Effects (Tables 3 and 4):

The within modality data summarised in Table 3, shows that the three Stroop task modalities appear to induce differential patterns of activation in the PFC. This does not appear to be the case in the CC. In the between modality comparisons (Table 4), when comparing the BOLD response in the congruent and neutral conditions, no regions were activated to a greater extent by the colour modality than by the number or shape modalities. After exclusion of task difficulty effects, this pattern of results remained the same. In contrast, the neural facilitation effect was greater in the number modality than in the shape modality in both the left superior temporal gyrus and the left superior frontal gyrus. These two regions remained more active in the number modality than in the shape modality when controlling for task difficulty effects. In addition, in the facilitation comparison, the number modality activated the right inferior parietal lobule and the left superior temporal gyrus to a greater extent than the colour modality, although these activations did not survive controlling for task difficulty effects. In the shape modality, the precuneus and right cerebellum were activated to a greater extent in this contrast than in the colour modality, although only precuneus activity was still greater after controlling for task difficulty. Finally, the facilitation contrast activated the right vlPFC (BA 10/11) and the right cuneus to a greater extent in the shape modality than in the number modality, although neither of these activations remained significant after excluding regions activated by task difficulty.

The Effect of Task Relevant Modality Upon Neural Interference Effects (Tables 3 and 4):

The within modality data summarised in Table 3, again shows that the three Stroop task modalities appear to induce differential patterns of activation in the PFC and that this does not appear to be the case in the CC. Table 4 summarises the corresponding between-modality comparisons for this contrast. When comparing the BOLD response in the incongruent and neutral conditions, the left dlPFC (BA 8/9) was activated to a greater extent in the colour modality than in the number modality and remained so after exclusion of task difficulty effects. In this contrast, no regions were activated to a greater extent in the colour modality than in the shape modality, in the number modality than in the shape modality, in the number modality than in the colour modality or in the shape modality than in the colour modality. After removing the effects of task difficulty indicated by performance accuracy differences, this pattern of results did not change. In the shape modality, the right lateral OFC (BA 47) and left dlPFC (BA 8) were activated to a greater extent in this contrast than in the number modality, and both these regions of activation remained significant after controlling for task difficulty effects.

Region of Interest Analyses:

In the cognitive ACC ROI there were no significant effects of modality in the facilitation contrast ($F(2,39)=1.19$, $p=0.32$) or the interference contrast ($F(2,39)=0.40$, $p=0.67$). In the dlPFC ROI there was no significant effect of task modality in the facilitation contrast ($F(2,39)=0.84$, $p=0.44$), but the effect of modality in the interference contrast was significant at $p<0.05$ ($F(2,39)=4.29$, $p=0.02$). Post hoc analyses determined that the mean t statistic in the interference contrasts of the colour and shape modalities were both greater than that in the number modality ($p=0.03$ and $p=0.05$ respectively).

Discussion

Task Relevant Modality Effects in the Prefrontal Cortex.

When comparing regions activated by the incongruent and neutral conditions, there were differential effects of task relevant modality within the PFC although not in the ACC. Before activations related to task difficulty were excluded, the colour modality activated the dlPFC more than the number modality and the shape modality activated the dlPFC and lateral OFC more than the number modality. Even when the effects of task difficulty were excluded, these particular modality effects remained. In the original neuroimaging study of the number modality, Bush et al. (1998) did not report dlPFC activation, which in combination with the prevalence of dlPFC activation in previous colour modality studies, supports the current study’s findings of greater interference-related dlPFC activation in the number modality than in the colour. Furthermore, the ROI analyses of the effect of task modality on the interference contrast revealed significantly greater dlPFC activity in the colour and shape modalities compared to the number modality. The data therefore suggest that the effect of task modality upon mediation of the Stroop interference effect may take two forms: (i) increased activation of regions well known to mediate performance of the Stroop task (i.e. the dlPFC) and (ii) increased activation of regions not previously known to mediate performance of the Stroop task (i.e. the lateral OFC).

It is thought that the PFC may play a role in imposing the attentional set necessary to selectively attend to the sources of information that are task-relevant (Banich et al., 2000). Since by the very nature of the tasks participants had to attend to different task-relevant attributes in each modality, it is highly likely that participants engaged different forms or strengths of selective attention and therefore recruited different aspects of the PFC. Behavioural evidence lends further weight to the idea of modular processing of different versions of typical inhibitory tasks. From their analysis of the construct validity of labelling three selective attention paradigms as testing ‘inhibition’, Shilling, Chetwynd and Rabbitt (2002) found no evidence that individuals who where particularly sensitive to interference on one task were also sensitive to interference on the others. Accordingly, they concluded that in each of their three tasks, the label ‘inhibition’ referred to slightly different phenomena. This conclusion could apply to cross-modality comparisons of the neural mediation of inhibition tasks such as the Stroop task. In the current study’s colour Stroop task, the task relevant and irrelevant information are one and the same entity. In contrast, in the number Stroop task they are not part of a single object, but are part of the same group unit. In the shape Stroop task the nature of the inhibitory process may be different again, since the task relevant and irrelevant information are two separate objects, albeit displayed in a closely associated manner.

The existence of task modality effects on PFC activation are given further credence by studies of other tests of selective attention, including variants of the classic flanker task. In contrast (see below) ACC activation does not appear to be affected by task modality (Hazeltine, Bunge, Scanlon, & Gabrieli, 2003). Prior to this study, functional specialization of the PFC in Stroop task paradigms has not received a great deal of explicit attention apart from studies by Banich et al. (2000a & 2000b). The current study's findings provide further support for Banich et al.'s contention that different subdivisions of the PFC are activated according to the nature of the task relevant information attended to, i.e. that its organisation is modular. The current data extend Banich et al.'s findings, by demonstrating task-relevant attentional set modularity according to a wider range of modalities, including the number or counting Stroop task, a variant of the Stroop task created by Bush et al. (1998) specifically for the fMRI environment. This study therefore solidifies the generalisability of the modular hypothesis of PFC activity. By dissociating the 'true' existence of modular PFC mediation of selective attention from the confounding combination of modality and task difficulty, only now can claims of differential PFC activity according to the nature of the task-relevant information be made with any certainty.

Due to overlap in regions of the brain activated by selective attention paradigms such as those reviewed in the introduction, the predominant view has been that selective attention is mediated in a unitary manner and by single circumscribed locations within the PFC and CC. Those who have favoured this position may argue against fully modular PFC activity. Of relevance to these suggestions, research in primates has proposed that the PFC may have a global role in a process that holds representations of stimulus information 'on-line', with independent analysis of visual and spatial information in adjacent PFC regions (Wilson, Scalaidhe, & Goldman-Rakic, 1993). If this model were applicable to humans, it could explain both the previously documented overlap in PFC activity associated with performance of these varied selective/inhibitory attention tasks AND evidence such as that from the current study, of modular task-relevant modality effects. A combination of modular and modality-common activation may be the best explanation of the PFC's behaviour when we attempt to engage in selective attention. This hypothesis deserves to be explored fully.

Although the OFC is still classed as part of the PFC, most previous studies do not report its activation (but see Bench et al.,1993). Use of an acquisition sequence designed to enhance OFC imaging, with the reduction in susceptibility artefacts by iPAT, and improvements in signal detection afforded by the multi-channel head coil and thin slices, may have combined to highlight activity in a region not previously associated with mediation of the Stroop task. That the lateral OFC was activated to such an extent in the shape modality (and not in the colour or number modalities), becomes less surprising when one bears in mind the literature supporting this region's association with other tests of selective attention to shapes or objects (Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991; Nagahama et al., 1998). The lateral OFC's relatively low activation in the number modality perhaps reflects the lack of association between this region and numerical operations (Delazer et al., 2003; Kawashima et al., 2004). Evidence from other cognitive paradigms suggests that the lateral OFC may be involved in processes quite similar to those required when performing Stroop tasks, i.e. inhibitory control and the ability to make behavioural choices (Elliott, Dolan, & Frith, 2000). Inhibitory selective attention may well be a more complex cognitive phenomenon than it might at first appear. Bearing in mind the OFC's well known role in emotion processing (e.g. Kringelbach & Rolls, 2004), a possible role may be that it modulates attentional set related activity in dorsolateral PFC regions according to emotion and mood influenced decision making. The data suggest once more that more diverse regions of the

PFC may contribute to selective inhibition than previously suspected. Future neuroimaging studies of the Stroop task may need to consider this phenomenon to a greater degree than before, particularly as the standard of neuroimaging technology increases.

The BOLD Response to Congruent Stroop Task Stimuli.

Once the effects of task difficulty were excluded, the shape Stroop task no longer activated the vlPFC more than the number Stroop task in the facilitation contrast. This difference in vlPFC activation can therefore be attributed to between-modality differences in task difficulty rather than any direct effect of task modality. This result is in keeping with the findings of Barch et al. (1997) who have previously demonstrated an association between vlPFC activation and increasing task difficulty. When comparing regions activated by the congruent and neutral conditions, and when controlling differences in task difficulty, there were therefore no differential effects of modality within the PFC or ACC.

Previous cross-modality comparisons of the effects of task-relevant information on regional brain activity have ignored facilitation processes in inhibition tasks. The current study provides new evidence as to how the neural mediation of facilitation and interference aspects of inhibition might differ. Whilst it may not be obvious that relative to the neutral condition, processing of congruent stimuli engenders conflict and therefore might also require contributions from the PFC, conflict (albeit of a different form) may still exist in determining whether to attend to the ink colour or the colour word dimension. In the incongruent relative to the neutral condition, conflict has a different form, that of semantic incongruency between the ink colours and colour words etc. In the currently available literature, it is difficult to discern reliable differences between the regions recruited to process congruent and incongruent stimuli, particularly since many studies have not included the facilitation comparison. Carter et al. (1995) published one of the few reports that have included this comparison. They predicted that activity of regions involved in attentional control (such as the PFC and ACC) would be low in this comparison due to what they viewed as a lack of interference (although see note above). Although it was admittedly less active in the congruent compared to the incongruent condition, amongst the regions activated more by the congruent than neutral condition were various ACC foci. Referring to the absence of facilitation effects being useful in differentiating between the performance of normal participants and those with certain neuropsychiatric disorders, they suggest that understanding the neural mediation of facilitation effects could increase our understanding of the neural bases of attentional dysfunctions in these patient groups. According to Macleod and MacDonald (2000), Stroop task facilitation and interference represent two distinct cognitive processing mechanisms. One could reasonably extrapolate from their conclusions that facilitation and interference are correspondingly processed by different neural mechanisms too. The current study’s findings that the modular mediation of selective attention in the PFC that exists in the interference contrast is not paralleled in the facilitation contrast provides support for the suggestion that these two components of Stroop task performance are independent cognitive processes which may also be subserved by distinct neural mediators. Banich et al. (2000) too suggest that the incongruent condition requires more PFC activity than the congruent condition due to an increased need for selective attention, but under the hypothesis that differences between facilitation and interference are best described as differences in the degree to which a single inhibitory function is recruited. It is possible that modality effects upon the mediation of selective attention in the PFC only emerge when the attentional demands rise above a certain threshold (and the potential for between-modality variability increases), below which PFC activation differences are negligible.

- Lack of Modality Effects in the Anterior Cingulate.

That there were no differential effects of task modality upon ACC activation in either the main analyses or the supplementary ROI analyses initially seems surprising considering the evidence of functional specialization in this region (e.g. Gruber et al., 2002). However, in accordance with the results of the current study, Barch et al. (2001) did not observe differential ACC activation according to either response modality or task modality. Whilst there is some evidence that the ACC is involved in task-relevant control of attention, the majority of evidence suggests that it is involved in error detection, or the monitoring of competition between processes that conflict during task performance (Holroyd et al., 2004), during which it signals the extent to which attentional control is required (Botvinick, Braver, Barch, Carter, & Cohen, 2001). If the ACC's role in Stroop-like inhibition tasks is that of error detection, then once between-modality differences in task difficulty are removed and the influence of errors thereby reduced, these theories might predict that there would be little remaining differential ACC activity. The lack of pre-task difficulty differential ACC activity precludes bringing the current study's data to bear on this issue. However, since the existence of conflict is also constant across modalities, a lack of modality-related differential ACC activity could also be interpreted as supporting Cohen et al.'s conflict monitoring theory of ACC function. Based on the distinction between the roles of the PFC (maintains cognitive set and attentional demands specific to the task) and ACC (may monitor response conflict) (MacDonald, Cohen, Stenger & Carter, 2000), Hazeltine et al. (2003) considered that the presence of material-dependent PFC activity and lack of ACC activity specificity in their study reflected an arrangement whereby cognitive control was implemented by material-specific modules and response conflict was monitored by a generic system. The overlap in dlPFC activation by different task modalities (reviewed above and in the introduction), Hazeltine et al. and the current study's finding of material-independent ACC activity, along with Banich et al. and the current study's finding of modular dlPFC activity suggest (i) generalised selective attention processes in the PFC and ACC, supplemented by (ii) modular dlPFC activity specific to the nature of the task-relevant information.

The Effects of Task Difficulty

As suggested by participants' debriefing comments, analyses of the behavioural data revealed that although the experimental designs were closely matched, the three modalities were not of equal task difficulty. Compared to the number Stroop task, participants were less accurate when performing the colour and shape Stroop tasks and their reaction times were slower. Indeed, both the shape and colour Stroop tasks incorporate a level of cognitive complexity that the number Stroop task does not and which may have contributed towards differences in task difficulty; namely the requirement to learn which response button is associated with which colour or shape. It is known that increased task difficulty can lead to increased arousal and /or frustration (e.g. Hong, 1999), and that it can also increase concentration (e.g. Karatekin, 2004), which could variously be manifest as increased attention or task engagement, greater effort being expended to detect errors, monitor conflict etc. Thus in a general sense, increased task difficulty could lead to greater recruitment of executive functions conducive to performing a more difficult task (e.g. Butter, 2004): i.e. top-down control over attention. In studies of attention processes in particular, increased task difficulty or complexity is associated with increased activity in both the PFC and ACC (Duncan & Owen, 2000; Paus, Koski, Caramanos, & Westbury, 1998), which of course, are both known for their role in the mediation of the Stroop effect. As a result, one might expect that a low difficulty task such as the number Stroop task may activate the ACC and PFC to a lesser extent than the colour or shape Stroop tasks. By attempting to separate out true modality effects from those of task difficulty, unlike previous reports (which erroneously perhaps, assumed no difference), the current study was able to identify task-relevant modality effects unconfounded by between-modality differences in task difficulty.

Selective attention to incongruent stimuli in the colour and shape modalities specifically activated a dlPFC region on the border of Brodmann's areas 8 and 9 to a greater extent than in the number modality and significantly greater dlPFC activation was noted in these modalities in the ROI analyses. This region is popularly associated with the mediation of working memory, particularly when working memory must be continuously updated (Veltman, Rombouts, & Dolan, 2003). One interpretation is that this higher dlPFC activity in the colour and shape modalities could indicate that those modalities require greater working memory resources than the number modality. Whilst the Stroop task primarily tests selective attention, it could be argued that working memory is involved since participants are required to maintain the response button coding system in their mind, constantly remember to inhibit their natural tendency to read the words in the task-irrelevant dimension, remember their intended response until they have pressed a response button, and rehearse their intended response so as to override how the automatic process of word reading is incorrectly leading them to respond. Conceptualised in this manner, working memory is not wholly equivalent to task difficulty. Even after the exclusion of task difficulty effects, the number modality may be of lower working memory load than the other two modalities because of its simpler button coding system. Equal practice was given on the button coding systems in each modality, but having done this does not negate differences in response modality ... httonaeons8(itwhieacn eac(syste9(ry ihe)]TJ0.0008 T -0.000

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coding system complexity are unlikely to be the sole explanation of between modality effects, since differential dlPFC activation was not observed in the facilitation contrasts, yet within each modality the response button coding system was the same for both the facilitation and interference contrasts.

With regards other consequences of the differences in complexity between the button coding systems, and their implications for CC and PFC activity, recent interest in the connections between the ACC and motor system (e.g. Picard & Strick, 1996) has identified the existence of three motor sites within the CC as a whole, and van Veen, Cohen, Botvinick, Stenger and Carter (2001) have suggested that these regions of the CC are intimately associated with conflict at the response level (as opposed to the stimulus level). Such a theory might predict that between-modality differences in response coding system complexity might manifest themselves as differential activity within these CC motor regions. The quantitative between modality comparisons did not reveal any differential activity within the CC though (i.e. including these cingulate motor regions), suggesting that this influence can be further discredited.

Conclusions

Prior evidence suggests common regions of activation in the ACC and dlPFC for a variety of tests of selective attention. Across quite different modalities in the current study, it appears that the nature of the task relevant information to be attended to has a modular effect on the neural mediation of selective attention in the PFC, but not the ACC. The results of this study also suggest that task difficulty may artificially exaggerate some differences in the neural mediation of selective attention tasks, although exclusion of task difficulty effects does not alter the presence of modularity effects within the dlPFC. It is therefore likely that generalised attention and conflict monitoring processes operate in the dlPFC and ACC respectively, but that in the dlPFC these are supplemented by modular activity according to differences in the nature of the attentional set required. Differential activation is unlikely in the ACC if conflict-monitoring requirements are consistent across modalities. In future studies notice should be taken of the fact that selective attention is not a unitary phenomenon and that effects of context such as modality need to be considered.

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